Renewable and Sustainable Energy Reviews 16 (2012) 911–920

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on entropy generation in natural and mixed convection heat transfer for energy systems

Hakan F. Oztop[a,b,*], Khaled Al-Salem[b]

[a] Deparment of Mechanical Engineering, Technology Faculty, Fırat University, TR-23119, Elazig, Turkey
[b] Department of Mechanical Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia

ARTICLE INFO

Article history:
Received 25 December 2010
Received in revised form 24 August 2011
Accepted 7 September 2011
Available online 4 October 2011

Keywords:
Entropy generation
Energy
Thermodynamics
Natural convection
Mixed convection

ABSTRACT

This paper reviews the second law analysis of thermodynamics in enclosures due to buoyancy-induced flow for energy systems. It defines entropy generation minimization or thermodynamic optimization. In addition, the article summarizes the recent works on entropy generation in buoyancy-induced flows in cavity and channels. Studies on mixed convection were also included in the study. Presentation was performed for flow in porous media and viscous fluid filled media at different shaped enclosures and duct under buoyancy-induced force.

Contents

1. Introduction

Entropy generation minimization or thermodynamic optimization is not an old technique. It is also components of exergy analysis [1]. The method of thermodynamic optimization or entropy generation minimization (EGM) is a field of activity at the interface between heat transfer, engineering thermodynamics, and fluid mechanics. The entropy generation minimization technique is based on the simultaneous application of the first law and the second law in analysis and design. Entropy can be used to distinguish between reversible and irreversible processes. It analysis can quantify the level of energy quality. In this paper we review the fundamentals of the method, its current status, and a few examples on natural convection studies.

The destroyed exergy is proportional to the generated entropy. Exergy is always destroyed, partially or totally: this is the statement made by the second law of thermodynamics. The destroyed exergy, or the generated entropy is responsible for the less-than-theoretical thermodynamic efficiency of the system.

First law efficiency of thermodynamics in a heat transfer engineering system is very much restricted. Thus, calculations using the second law of thermodynamics, which is related to entropy generation, are more reliable than first law based calculations. In almost all thermal systems, second law-based efficiency can be defined in terms of the ratio of actual thermal efficiency under the same conditions. Therefore, the second law of thermodynamics can be applied to investigate the irreversibility in terms of the entropy generation rate. Determination of entropy generation is also important to enhance system performance, because entropy generation is the measure of destruction of available work of the system [2–4].

* Corresponding author at: Tel.: +90 424 2370 0000x4222; fax: +90 424 241 5526.
E-mail address: hfoztop1@gmail.com (H.F. Oztop).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.09.012

Nomenclature

Be	Bejan number
C	concentration
FTI	fluid friction irreversibility
HTI	heat transfer irreversibility
k	thermal conductivity
Ns	total entropy generation
S	entropy
T	temperature
u, v, w	velocities
x, y, z	coordinates
$\dot{S}'''_G$	volumetric rate of entropy generation

Greek letters

μ	dynamic viscosity
ϕ	irreversibility ratio

The method relies on the simultaneous application of principles of heat and mass transfer, fluid mechanics, and engineering thermodynamics, in the pursuit of realistic models of processes, devices, and installations.

2. A brief theory

It is well known from the thermodynamics that heat transfer in the system results in thermodynamic irreversibility and it generates the entropy. The minimization of entropy is a method of optimization of the thermodynamic imperfections and fluid flow irreversibilities [5]. Thus, investigation of entropy generation and minimization in the heating systems is important to include irreversibilities into the thermodynamic analysis. Entropy is a measure of chaos and if there is entropy in a system, the quality of energy decreases. A system of high entropy is more chaotic or disordered than one of low entropy. For example, a field with papers scattered about has higher entropy than the field with the papers neatly piled [1]. A study of entropy generation in fundamental convective heat transfer was obtained by Bejan [6,7].

Entropy analysis involves the evaluation of the inputs, outputs, accumulations and creations of entropy for a considered system. It means that

$$\text{Entropy input} + \text{Entropy generation} - \text{Entropy output} = \text{Entropy accumulation} \quad (\text{change in the total entropy of the system}) \tag{1}$$

In above formulation, the entropy creation is identical to negentropy consumption and proportional to exergy consumption [1].

Entropy balance in the rate form is given by

$$\Delta\dot{S}_{\text{system}} = (\dot{S}_{\text{inlet}} - \dot{S}_{\text{outlet}}) + \phi \tag{2}$$

The local volumetric rate of entropy generation, $\dot{S}'''_G$ (W/m^{3}K), based on the second law of thermodynamics, is given for three dimensional flow as follows [8,9],

$$\dot{S}'''_G = \frac{k}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \frac{\mu}{T}\left[2\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right) + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2\right] \tag{3}$$

The first term on the right-hand side is due to heat transfer and the second term is due to viscous dissipation. It is well known that the viscous dissipation in the first law of thermodynamics is negligible in many engineering applications.

By adding mass transfer the equations [10],

$$\dot{S}'''_G = \frac{k}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \frac{\mu}{T}\left[2\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right) + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2\right] + \frac{RD}{C}\left[\left(\frac{\partial C}{\partial x}\right)^2 + \left(\frac{\partial C}{\partial y}\right)^2 + \left(\frac{\partial C}{\partial z}\right)^2\right] + \frac{RD}{T}\left[\left(\frac{\partial T}{\partial x}\right)\left(\frac{\partial C}{\partial x}\right) + \left(\frac{\partial T}{\partial y}\right)\left(\frac{\partial C}{\partial y}\right) + \left(\frac{\partial T}{\partial z}\right)\left(\frac{\partial C}{\partial z}\right)\right] \tag{4}$$

In above equation, C defines the concentration. Eq. (3) clearly shows that entropy generation in a convection heat transfer occur mainly heat transfer and fluid friction. Thus, an important parameter can be defined as irreversibility ratio. The definition of irreversibility ratio may enhance the understanding of the irreversibilities associated with the heat transfer and the fluid friction [5]. It is given as [6,7],

$$\phi = \frac{\dot{S}'''_{G,\text{fluidfriction}}}{\dot{S}'''_{G,\text{heattransfer}}}. \tag{5}$$

Carrington and Sun [38] investigated the second law analysis of combined heat and mass transfer for both internal and external flows. They found an equation for the entropy generation. The dimensionless Bejan number (Be) [11] is used in entropy studies. It can be used as the alternative irreversibility distribution [11],

$$Be = \frac{(\nabla T)^2}{(\nabla T)^2 + (\nabla \Psi)^2} \tag{6}$$

$Be \gg 0.5$ is the limit at which, heat transfer irreversibility dominates; $Be \ll 0.5$ is the opposite limit at which, irreversibility is dominated by fluid friction effects; and $Be \cong 0.5$ is the case wherein, heat transfer irreversibility and fluid flow irreversibility are of equal importance. Here also, integrating Bejan number yields global Bejan number [12],

$$Be_{\text{global}} = \iint_{\forall} Be\, d\forall = \int_0^1 \int_0^1 Be(X,Y)dXdY \tag{7}$$

Other fundamental studies on entropy generation in convective heat transfer and isothermal convective mass transfer [13], combined heat and mass transfer [14], counter flow heat exchangers for gas-to-gas applications [15], fundamental convective heat transfer [16], design optimization of thermal system [17] and irreversibilities in various duct [18]. Table 1 illustrates a summarize on fundamental studies of entropy generation.

3. Studies for natural convection in porous media filled systems

Natural convection in porous media has an important topic due to the day-by-day improvements of engineering in industry. There are many applications for this topic such as building materials, insulation technology, bioengineering, geothermal application, chemical technologies, filter design, etc. [19,20]. Entropy analysis is an effective method for studies on porous media to obtain system efficiency. Fundamentals of entropy generation in natural convection are defined widely by Baytas and Baytas [21]. Mahmud and Fraser [22] investigated the nature of heat transfer and entropy generation for natural convection in a two-dimensional circular

Table 1
Summary of fundamental studies on entropy generation in convective heat transfer.

Author	System	Topic
Rosen [1]	Different engineering systems	Second-law analysis
Bejan [2]	Different engineering systems	Second-law analysis in heat transfer
Bejan [6–9]	Different engineering systems	Fundamentals of exergy analysis, entropy generation minimization
Arpaci and Selamet [27]	Energy systems	Entropy efficiency
Carrington and Sun [38]	Combined heat and mass transfer in both internal and external flows	Second-law analysis
Bejan [15]	Heat exchanger design counter flow heat exchangers for gas-to-gas applications	Irreversibility
Tsatsaronis et al. [17]	Design optimization	Exergy
Naterer and Camberos	Simulation	Entropy and the second law
Prigogine [63]	Thermodynamics processes	Irreversibilities
Oztop [64]	Semicircular duct	Second law analysis
Amani and Nobari [73]	Curved pipes	Entropy generation
Chen et al. [67]	Vertical channel	Entropy generation
Hernandez et al. [74]	Fuel cell	Entropy generation analysis

section enclosure filled with porous media. In their work, the Darcy momentum equation is used to model the porous media. Results are presented in terms of Nusselt number, entropy generation number, and Bejan number. They found that for conduction regime, both average Nusselt number and the entropy generation number are independent of Rayleigh number variation. In convection-dominated regime, these parameters show an increasing tendency with increasing Rayleigh number. At high Rayleigh number, the near-wall magnitude of overall entropy generation rate is higher, but heat transfer irreversibility is higher at the center portion of the cavity. These are summarized in Fig. 1. By plotting Nusselt number and entropy generation number versus Rayleigh number. In their another study, the problem of entropy generation in a fluid saturated porous cavity for laminar magnetohydrodynamic natural convection heat transfer is analyzed by considering Darcy's law for porous media. Magnetic force is assumed acting along the direction of the gravity force. As boundary conditions of the cavity, two vertical opposite walls are kept at constant but different temperatures and the remaining two walls are kept thermally insulated. For a range of Rayleigh number ($Ra = 1–10^4$) and Hartmann number ($Ha = 0–10$), heat transfer, overall entropy generation rate, and heat transfer irreversibility are presented in terms of dimensionless Nusselt number (Nu), entropy generation number (Ns), and Bejan number (Be), respectively. Fig. 2, in their paper, presents Ns_{av} and Be_{av} for Fig. 2(a) and (b), respectively. These are function of Hartmann number at different Ra. Similar to the Nu_{av}–Ha profile characteristics, Ns_{av} is maximum at $Ha = 0$, decreases with increasing Ha and approaches an asymptote at higher values of Hartmann number. Magnitudes of Be_{av} are almost same for all Rayleigh numbers considered here at $Ha = 0$. Increases in the value of Ha have a tendency to slowdown the fluid movement inside the cavity, thus causing relative increases of heat transfer irreversibility (i.e., Be_{av}).

Baytas [11] performed a study to investigate the entropy generation due to buoyancy forces in an inclined porous cavity. He observed that when Rayleigh number decreases, heat transfer irreversibility begins to dominate the fluid friction irreversibility. The Bejan number is rapidly changed between 150° and 270°. The problem of entropy generation for unsteady natural convection and radiation in a tilted open-ended channel, submitted to uniform hot walls temperature and filled with an isotropic fluid saturated porous medium is outlined by Slimi [23]. In his study, Darcy flow model was used and viscous dissipation effects are taken into account. His results showed that the global heat transfer rate depends slightly on the viscous dissipation term but is strongly subordinate to the tilted angle. Moreover, the calculation of entropy generation maps is feasible and gives a measure of the degree of irreversibility of the convective flow. Recently, entropy generation due to buoyancy-induced convection and conduction in a right angle trapezoidal enclosure filled with fluid saturated porous medium has been performed numerically by Varol et al. [19]. In their case, the left vertical solid wall of the trapezoidal enclosure has a finite thickness and conductivity. The governing Darcy and energy equations are solved numerically using a finite difference method. Entropy generation is calculated by using the obtained velocities and temperature distributions from the computer code.

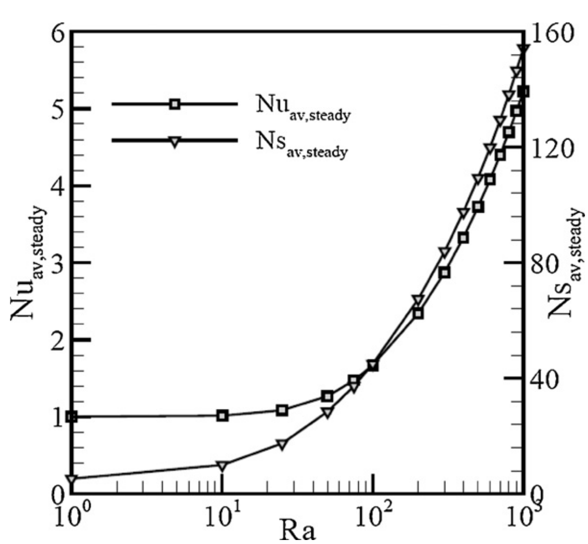

Fig. 1. Average Nusselt and entropy generation numbers as a function of Rayleigh number [5].

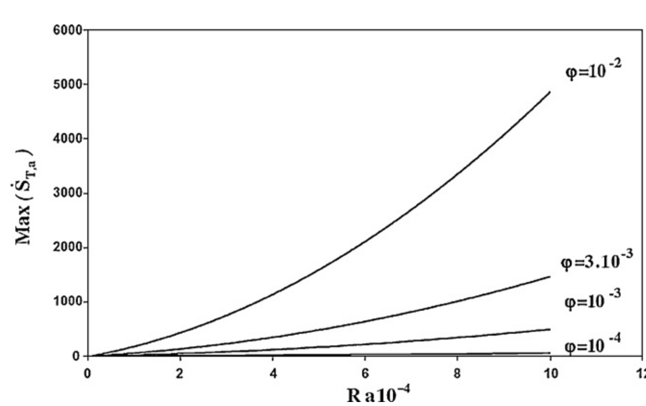

Fig. 2. (a) Average entropy generation number as a function of Rayleigh number. (b) Average Bejan number as a function of Rayleigh number [16].

Results are presented for the Bejan number, local and mean Nusselt numbers, streamlines, isotherms, iso-Bejan lines and entropy generation contours. It is found that the most important parameters on heat transfer and fluid flow are thermal conductivity ratio and dimensionless thickness of the solid wall of the enclosure. Thus, these parameters also generate entropy for the whole system. It is also observed that increasing the Rayleigh number decreases the Bejan number; however, heat transfer is an increasing function of Rayleigh number. Non-uniform heating effects are tested on entropy generation due to natural convection in a isosceles triangular enclosures at different positions by Varol et al. [24]. They found that both inclination angles and Rayleigh numbers make important effect on natural convection heat transfer, fluid flow and entropy generation. The highest entropy generation due to HTI and FFI and stream function are observed at $\varphi = 90^\circ$. Multiple cells were formed at this angle. Streamlines, isotherms and entropy contours are symmetric inside the enclosure for both $\varphi = 0^\circ$ and $\varphi = 180^\circ$.

In Zahmatkesh's [12] study, a numerical analyze was performed on the importance of thermal boundary conditions of the heated/cooled walls in heat transfer and entropy generation characteristics inside a porous enclosure, heated from below. Both the heating and the cooling are carried out uniformly and non-uniformly and the results are compared. He presents results in terms of streamlines, isothermal lines, iso-entropy generation lines, and iso-Bejan lines. Additionally, variations of average Nusselt number, global entropy generation rate, and global Bejan number are analyzed over a wide range of Darcy-modified Rayleigh number ($10 < Ra < 1000$). Inspection of the results indicates that thermal boundary conditions are of profound influences on the induced flow as well as heat transfer characteristics and possess prominent consequences on entropy generation rates. It is demonstrated that, the optimum case with respect to heat transfer as well as entropy generation could be achieved by non-uniform heating.

In another study of Baytas [25], the entropy generation in a saturated porous cavity for laminar natural convection is investigated by using the non-Darcy flow model and a thermal nonequilibrium model of the heat transfer between the fluid and the solid phases. His results demonstrated that the entropy generation due to viscous drag is very important for the non-Darcy flow model, and the high temperature difference between solid and fluid phases shows the importance of the thermal nonequilibrium model for porous media. He suggested that entropy generation for the thermal nonequilibrium and non-Darcy flow models should be considered for engineering design and thermodynamic optimization. Mahmud and Fraser [26] investigated the nature of entropy generation for natural convection in a square enclosure filled with porous media vibrating sinusoidally perpendicular to the applied temperature gradient in a zero-gravity field. They indicated that Gravity oscillation introduces a true periodic behavior to the Nusselt number, Bejan number, and entropy generation rate. The periodic response of these three parameters is synchronized with the forced acceleration, namely, having the same period as the forced acceleration. Table 2 gives a summary of the various theoretical investigations for entropy generation in porous media filled systems.

4. Studies for natural convection viscous fluid filled medium

In industrial application, natural fluids as air or water are used mostly. Thus, in the analyses, thermal properties of these fluids are taken into account to the analysis. Arpaci and Selamet [27] investigated the internal energy generation in case of buoyant turbulent flows. They developed a thermal model based on microscales flows for different parameters. Dagtekin et al. [28] performed a numerical study to investigate the second law analysis due to buoyancy-induced flow in a Γ-shaped enclosure. They investigated effects of geometrical ratio and Rayleigh number on entropy generation.

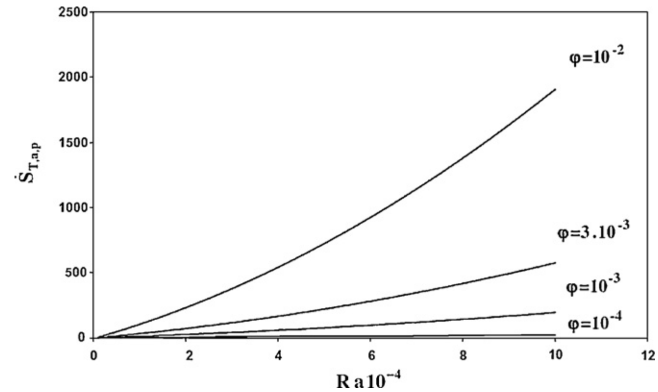

Fig. 3. Evolution of the maximum of the dimensionless total entropy generation versus Rayleigh number and distribution irreversibility ratio $\varphi = 10^{-4}$, 10^{-3}, 3.3×10^{-3} and 10^{-2} [30].

Influence of thermodiffusion on the birth of free convection in Rayleigh–Benard configuration was investigated by Platten and Chavepeyer [29]. They summarize the influence of thermodiffusion on free convection together with the way to use this mutual influence in order to experimentally deduce the value of the Soret effect. Magherbi et al. [30] studied the time-dependent natural convection and second law analysis of thermodynamics in a differentially heated enclosure using finite volume technique. They indicated that the total entropy generation has a maximum value at the onset of the transient state, which increases with the Rayleigh number and the irreversibility distribution ratio. They also found that entropy generation asymptotically tends towards a constant value at low Rayleigh numbers, whereas an oscillation of the entropy generation was observed for higher Rayleigh numbers, before reaching the steady state. Graphs of the maximum of the total entropy generation Max ($\dot{S}_{T,a}$) as function of Rayleigh number at different irreversibility distribution ratio φ are shown in Fig. 3. At low irreversibility distribution ratios (as low as $\varphi \leq 10^{-4}$) Max ($\dot{S}_{T,a}$) takes on small values even at high Rayleigh numbers. However, for $\varphi \leq 10^{-3}$, Max ($\dot{S}_{T,a}$) increases rapidly. Similar observations can be made about the evolution of the total entropy generation ($\dot{S}_{T,a}$) as a function of the Rayleigh number during the steady state as seen in Fig. 4.

Entropy generation in rectangular cavities with the same area but different aspect ratios is numerically investigated by Ilis et al. [31]. They used finite difference method and the energy and vorticity equations are solved line by line by employing the ADI method, whereas the stream function equation is solved point by point. It is found that for a cavity with high value of Rayleigh number (i.e., $Ra = 10^5$), the total entropy generation due to fluid friction and total entropy generation number increase with increasing aspect ratio, attain a maximum and then decrease. For all cavities with different aspect ratio, the total entropy generation increases with increasing Rayleigh number, though the rate of increase is different as seen in Fig. 5. For $Ra = 100$, the total entropy generation increases from the minimum aspect ratio (AR = 1) to the maximum aspect ratio (AR = 16) with the same order. For $Ra = 10^5$ and $\phi = 10^{-4}$, the total entropy generation for the AR = 16 cavity is less than that for AR = 9 due to the peak point of the fluid friction total entropy generation.

Mourad et al. [10] report a numerical determination of the entropy generation in doubly diffusive convection on 2D approximation in a square inclined cavity, filled with a fluid (assumed to be a perfect gas mixture). Their results showed that the total entropy generation increases with the thermal Grashof number

Table 2
Summary of investigations in porous media filled enclosures.

Author	Study	Method	Results and remarks
Mahmud and Fraser [16]	Magnetohydrodynamic free convection in a porous enclosure	Control volume based finite-volume method	In the absence of magnetic force, entropy generation rate is relatively higher in magnitude near two vertical walls
Mahmud and Fraser [22]	Free convection inside a two-dimensional circular porous enclosure	Control volume based finite-volume method was used. A non-staggered and non-uniform grid system is used with a higher mesh density near the walls	At high Rayleigh number, the near-wall magnitude of overall entropy generation rate is higher, but heat transfer irreversibility is higher at the center portion of the cavity
Zahmatkesh [12]	Free convection inside a circular porous enclosure with different boundary conditions	Control volume method of Patankar [62]	Entropy generation rate is likely to be the highest for uniform heating/cooling and the lowest for non-uniform heating
Baytas [25]	Porous square enclosure filled with a heat-generating solid phase	Non-equilibrium porous model Finite volume finite difference method	The entropy generation due to viscous drag is very important for non-Darcy flow model as well as high temperature difference
Baytas [11]	Tilted saturated porous cavity	Finite difference control method of Patankar [62]	Inclination angle of cavity makes important effect on degree of irreversibility
Varol et al. [19]	Right-angle trapezoidal enclosure	Finite difference method	Inclination angle of the inclined wall of trapezoidal geometry affects the entropy generation
Slimi [23]	Tilted saturated porous channel		Entropy generation maps is feasible and gives a measure of the degree of irreversibility of the convective flow
Mahmud and Fraser [49]	Square porous enclosure with vibration	Control volume based finite volume method	At the lower extreme of the gravity oscillation Nu_{av} and Ns_{av} is minimum and Be_{av} is maximum

and the buoyancy ratio for moderate Lewis numbers. Locally, the irreversibility due to heat and mass transfer are nearly identical and are localized in the bottom and the top of the heated and the cooled walls respectively. Entropy generation due to natural convection has been calculated for three radii and a wide range of Rayleigh numbers for an isothermal cylinder by Abu-Hijleh et al. [32]. They indicated that, for air, entropy generation was predominantly due to conduction while the contribution of viscous dissipation was negligible. As the Rayleigh number increased, total entropy generation increased. As the radius of the cylinder increased, total entropy generation decreased.

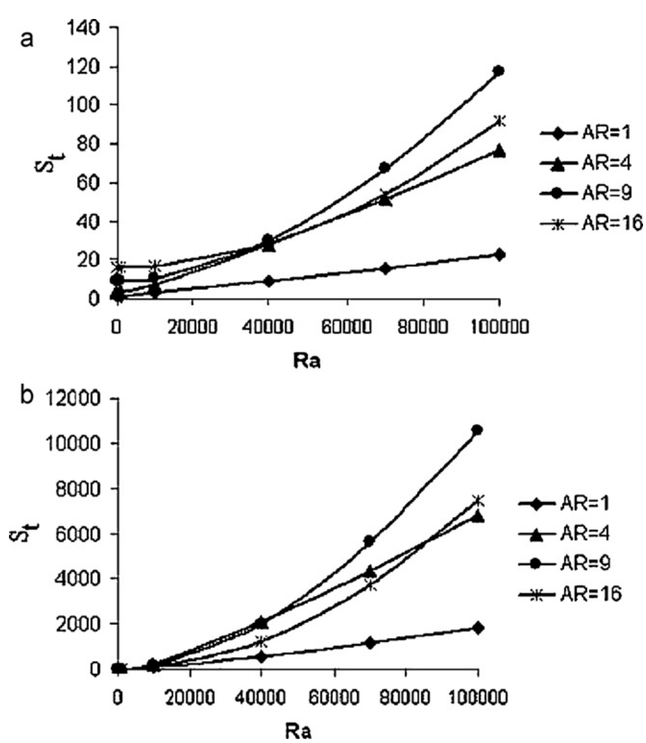

Fig. 4. Variation of the dimensionless total entropy generation in steady state versus Rayleigh number and distribution irreversibility ratio $\varphi = 10^{-4}$, 10^{-3}, 3.3×10^{-3}, and 10^{-2} [30].

The optimization in an inclined square enclosure for minimum entropy generation was analyzed by Baytas [33]. Based on that study, the local heat transfer irreversibility and the local fluid friction irreversibility change by the inclination angle and the minimum entropy generation depends considerably on the inclination. Numerical prediction of local and total entropy generation rates for natural convection of air in a vertical channel symmetrically heated with a uniform heat flux was studied by Andreozzi et al. [34]. They found that global entropy generation increases with both aspect ratio and Rayleigh number increase. These values have been correlated as function of Ra and L/b; the correlation obtained by means of the least square method is

$$\log\ S^{*}_{X,Y} = -13.2 + 1.91 \log Ra + 0.045 \left(\frac{L}{b}\right) \tag{8}$$

In above equations,

$$r^2 = 0.999 \quad \text{and} \quad 5 \le \frac{L}{b} \le 20 \times 10^3 \le Ra \le 10^6. \tag{9}$$

Erbay et al. [35] analyzed the thermodynamic irreversibilities due to natural convection in a square enclosure. Erbay et al. [36,37] investigated entropy generation with a single discrete heat source on the vertical wall of a cavity. Their work focused on the transient development of the flow and temperature fields and instantaneous entropy generation distributions during the transient stages.

Shuja et al. [5] made a numerical work on natural convection in a square cavity with a heat generating body by including entropy consideration. They solved both convection and conduction (conjugate) mode of heat transfer to simulate cooling of micro-electronic equipments. They compared the effects of working fluid as air and water and found that the flow developed in the cavity due to natural convection has almost the same mode of velocity fields for air and water. Cooling performance of heated body is related with location of the body. The entropy generation due to heat transfer is relatively lower for the solid body located in left bottom and right top corners of the cavity. It attains high values in the case of fluid friction. It is an interesting result that the entropy attains higher values in the case of air as compared to the case for water. It means that the heated solid body losses more heat in air than in water for the indicated simulation conditions. Table 3 illustrates the total entropy generation in the cavity due to HTI and FFI. In The case of air total entropy generation due to heat transfer and fluid friction

Table 3
Total entropy generated in the cavity for various cases [45].

Working Fluid	Solid position	Entropy generated (J/K) due to			
		Heat transfer	Fluid friction	Total	Irreversibility ratio (ϕ)
Air	Bottom	2.379×10^{-9}	$6.377 \times 10^{-1\circ}$	3.017×10^{-9}	0.2680
	Center	3.228×10^{-9}	1.286×10^{-10}	3.357×10^{-9}	0.0399
	Top	2.419×10^{-9}	2.797×10^{-10}	2.698×10^{-9}	0.1160
Water	Bottom	3.238×10^{-11}	1.170×10^{-10}	1.494×10^{-10}	3.6100
	Center	5.884×10^{-11}	2.020×10^{-11}	7.905×10^{-11}	0.3430
	Top	2.560×10^{-11}	5.024×10^{-11}	7.584×10^{-11}	1.9600

attains higher values as compared to that for water. In addition, the total entropy generation due to heat transfer has maximum value when the solid body is at the center of the cavity while the total entropy generation due to fluid friction has a minimum value at this location. This may indicate that fluid motion generated close to the solid body is equally distributed in the vicinity of all surfaces of the solid body, which results in a relatively low velocity flow field. On the other hand, the increase in total entropy due to heat transfer is not only because of the convection effect, but the conduction effect as well. From the table, the irreversibility ratio is minimum when the solid body is located at the center of the cavity.

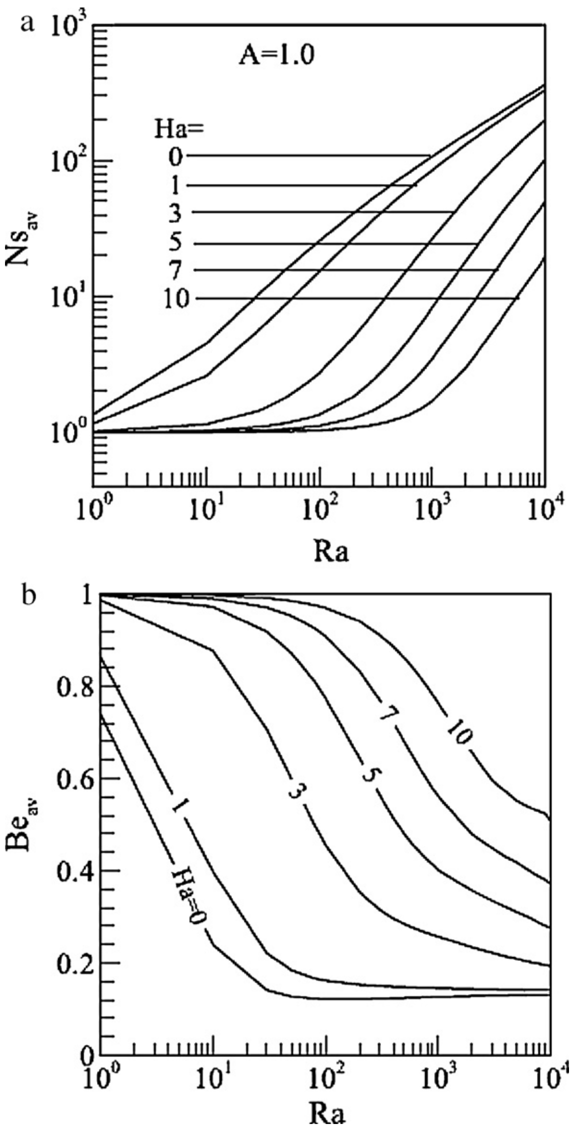

Fig. 5. The changes of total entropy generation with Rayleigh number for cavities with different aspect ratios (a) $\Phi = 10^{-4}$ and (b) $\Phi = 10^{-2}$ [31].

Varol et al. [39] studied the forecasting of entropy generation of laminar natural convection in a partially cooled square cross-sectional room has been performed using support vector machines (SVM). The two-dimensional room was modeled as floor heating story with a window. Forecasting of entropy generation due to fluid friction irreversibility (FFI) and heat transfer irreversibility (HTI) were made with known values for unknown parameters using SVM. Thus, calculation time was extremely reduced and values were obtained even for non-convergence cases.

Recently, Mukhopadhyay [40] made a numerical work to analyze entropy generation due to natural convection in square enclosures with multiple discrete heat sources. He examixed the heaters of equal length and strength, the effects of Rayleigh number and heater position on flow and temperature fields and local entropy generation. He indicated that for heaters of equal length and strength ratios, placement of the heaters close to the mid-plane of the cavity is most undesirable as both peak temperature and entropy generation are maximized. On the other hand, placing the heaters very close to the walls or at a dimensionless spacing of about 0.5 is most desirable as both these quantities are minimized.

Yang et al. [41] performed the second law analysis of thermodynamics on the laminar film condensation of pure saturated vapor flowing in the direction of gravity on an ellipsoid with variable wall temperature. They found that entropy generation increases with ellipticity. Furthermore, the irreversibility due to finite temperature difference heat transfer dominates over that due to condensate film flow friction and the local entropy generation rate decreases with increasing ellipticity in the upper half of ellipsoid. Abu-Hijleh et al. [42] made a numerical prediction of entropy generation due to natural convection from a horizontal cylinder. Fig. 5 shows that an increase in Ra_D, i.e., a higher temperature difference between the cylinder and surroundings, results in an increase in S_{gen}. The main conclusion from Fig. 5 is that the use of larger cylinders results in significantly lower entropy generation for the same value of Ra_D due to a lower temperature difference. A larger cylinder has a lower tangential temperature gradient, which reduces the contribution from the second component in the conduction part of Eq. (8). Increased cylinder size results in an increase in viscous dissipation in Eq. (8). It should, however, be noted that the second term of Eq. (8) was negligible even at the largest r_o for the greatest Ra_D. Thus, there was no appreciable increase in S_{gen} at large r_o due to viscous dissipation. Analysis of local entropy-generation profiles showed that the location of maximum entropy generation depends on the size of the cylinder. For $r_o = 10^{-3}$ m, maximum entropy generation occurred in the plume region, at the top of the cylinder. For $r_o = 10^{-1}$ m, maximum entropy generation occurred in the inflow region, at the bottom of the cylinder. For $10^{-1} > r_o > 10^{-3}$, the contributions from both the inflow and plum regions were of the same order. We may manipulate the flow in regions of low local entropy generation with minimal adverse effects on the total irreversibility of the component. Jery et al. [43] performed a study on influence of an external oriented magnetic

Table 4
Summary of the calculation of entropy due to natural convection in different enclosures.

Authors	Geometry	Method	Results and remarks
Abu-Hijleh and Heilen [46]	Heated rotating cylinder	Elliptic system of PDEs are solved by explicit hybrid scheme	The total entropy generation increases with the increase of both Reynolds number and buoyancy parameter but decreases as the cylinder radius increases
Abu-Hijleh et al. [32]	Heated isothermal cylinder in oil	Elliptic system of PDEs are solved by explicit hybrid scheme	Including the viscous dissipation term had minimal effect on Nusselt number and total entropy generation
Abu-Hijleh et al. [42]	Natural convection from a horizontal cylinder	Equations are solved in streamfunction–vorticity formulation	As the radius of the cylinder increased, total entropy generation decreased.
Andreozzi et al. [34]	Vertical channel symmetrically heated at uniform heat flux	Numerical solutions of the elliptic momentum and energy equations are carried out with the stream-function–vorticity method	Global entropy generation increases with both aspect ratio and Rayleigh number increase
Baytas [33]	Natural convection in inclined cavity	Finite volume technique	An optimization has been made to obtain minimum entropy generation
Mukhopadhyay [40]	Natural convection in square enclosures with 2 multiple discrete heat sources	The governing equations were discretized using SIMPLER algorithm of Patankar [62]	The dominant contribution to entropy generation comes from heat transfer irreversibilities, with fluid friction accounting for only a small fraction of the total entropy generation
Famouri and Hooman [52]	Natural convection by heated partitions in a cavity	FORTRAN code and the commercially available CFD-ACE software.	While fluid friction term has nearly no contribution to entropy production, the heat transfer irreversibility increases monotonically with the Nusselt number and the dimensionless temperature difference
İlis et al. [31]	Rectangular cavity with differentially heated vertical walls	Finite difference technique	For a cavity with high value of Rayleigh number (i.e., *Ra* = 105), the total entropy generation due to fluid friction and total entropy generation number increase with increasing aspect ratio, attain a maximum and then decrease.
Magherbi et al. [30]	Entropy generation at the onset of natural convection in a differentially heated enclosure	Of the control volume finite-element method (CVFEM)	The total entropy generation has a maximum value at the onset of the transient state, which increases with the Rayleigh number and the irreversibility distribution ratio
Mourad et al. [10]	Numerical determination of the entropy generation in doubly diffusive convection on 2D approximation in a square inclined cavity	Control volume finite-element method (CVFEM)	Total entropy generation increases with the thermal Grashof number and the buoyancy ratio for moderate Lewis numbers
Erbay et al. [37]	An analysis of the entropy generation in a square enclosure with partial heating	Finite volume method (FVM) coupled with power law scheme for the convective terms	The irreversibilities are dominant due to heat transfer whereas fluid friction irreversibilities have been found negligible as it is expected for the natural convection
Shuja et al. [5]	Square cavity with heat generating body		The entropy generation due to heat transfer is relatively lower
Mahmud and Sadrul Islam [53]	Wavy enclosure	Finite volume method	Wave ratio is an important parameter on entropy production
Varol et al. [54]	Partially heated isosceles triangular enclosures	Finite difference method	Length of partial heater the most effective parameter on entropy generation
Varol et al. [55]	Conjugate natural convection in enclosures	Finite difference method	Thermal conductivity ratios and thickness of solid wall become effective on entropy production
Mahmud and Fraser [56]	Mixed convection-radiation interaction in a vertical channel	Analytical study with reasonable simplifications	Irreversibility due to the heat transfer and/or fluid friction become zero at idle points
Bassam [58]	Cylinder	Streamfunction-vorticity	Entropy increases with *Ra* number
Yilbas [57]	Cavity heated from bottom	Finite volume method	Temperature difference play important role on entropy generation
Mahmud et al. [59]	Vertical channel	Analytical solution	For positive value of heat generation/absorption parameter, entropy generation rate is higher than the negative value of same magnitude
Oliveski et al. [69]	Enclosures	General methods	Entropy generation is applied for natural convection
Kaluri and Basak [68]	Differentially heated cavities	Finite element method	Prandtl number plays important role on entropy generation
Saleem et al. [70]	Marangoni convection	Finite difference method	Entropy generation rate increases with the increase in the Marangoni number
Kaluri and Basak [71]	Discretely heated square cavity	Finite element method	High thermal mixing may not be the optimal situation for achieving uniform temperature distribution based on entropy production
Basak et al. [72]	Wide variety of thermal boundary conditions	Galerkin finite element method	Thermal boundary conditions are affected on thermal mixing, heat transfer and entropy generation

field on entropy generation in natural convection for air and liquid. They studied the steady-unsteady states mass, momentum and entropy equation for different inclination angle of the magnetic field and Pradntl number. At local level and for relatively higher thermal Grashof number ($Gr_T = 10^5$), entropy generation distribution is strongly dependent on magnetic field direction, magnitude of irreversibility lines increases up to 30°, then gradually decreases. No entropy is generated in the cavity center. Table 4 summarizes the various investigations for entropy generation in viscous fluid filled systems.

5. Entropy generation due to mixed convection

Mixed convection heat transfer occurs for both natural and forced convection present in a system. In this case, Richardson number (Gr/Re^2) becomes effective. Entropy places important role in this type of heat transfer regime due to heat transfer and fluid friction.

Narusawa [44] studied the second-law analysis in a rectangular duct for mixed convection regime. The simulation of mixed convection in a square cavity with protruding body having different aspect ratios was performed by Yilbas et al. [45]. Abu-Hijleh and Heilen [46] studied the entropy generation due to laminar mixed convection from an isothermal rotating cylinder for three cylinder radii and covered wide ranges of Reynolds number and buoyancy parameter. They observed that entropy generation increased as the Reynolds number and buoyancy parameter increased and it decreased as the cylinder radius increased. For the same combination of Reynolds number and buoyancy parameter, entropy generation was mainly due to thermal effects at small cylinder radii and due to viscous effects at large cylinder radii. Abbassi et al. [47] analyzed the entropy generation in Poiseuille–Benard channel flow. He found that the maximum entropy generation is localized at areas where heat exchanged between the walls and the flow is maximum. There is no significant entropy generation is seen in the main flow. In the similar manner, Nourullahi et al. [48] interested by the issue of entropy generation and Nusselt number in Poiseuille–Benard channel flow are analyzed by solving numerically Navier–Stokes and energy equations with the use of the classic Boussinesq in compressible approximation. Their result showed that the Nusselt number changes very slightly and it is almost constant for low values of inclination angle. It decreases for higher values of inclination angle. The entropy generation due to heat transfer is localized at areas where heat exchanged between the walls and the flow has a maximum value, while the entropy generation due to fluid friction is maximum at areas where the velocity gradients are maximum such as vortex centers. In other words, the inclination angle is a good parameter to control entropy generation in the presence of buoyancy forces. Mahmud and Fraser [49] focused on magnetohydrodynamic mixed convection through a vertical channel packed with fluid saturated porous substances by applying first and second laws of thermodynamics to analyze the problem. They solved governing equations analytically under reseasonable simplifications for different parameters such as Hartmann number, Plank number, Richardson number and group parameter (Br/Π). They found that the entropy generation number is characterized by a concave shaped profile and is symmetric about the channel centerline for a symmetrical temperature boundary condition. Radiation and mixed convection parameters have a more dominating influence on entropy generation rate than porous-magnet and group parameters. Expressions for the idle points of entropy generation are derived and their location(s) are determined. Irreversibility due to the heat transfer and/or fluid friction becomes zero at these idle points. Shohel and Roydon [50] did a similar work on mixed convection–radiation interaction in a vertical channel by calculating entropy generation. Another application has been performed by Cheng et al. [51] on entropy production in mixed convective flow in a vertical channel with transverse fin arrays.

6. Entropy generation of natural convection in nanofluid filled enclosures

Addition of nanoparticles (Al_2O_3, Cu, Ag, Au, CuO, TiO_2, etc.) of any material into base fluid such as water, glycerol, etc. is called as nanofluid. In this way, heat transfer of fluid is enhanced due to higher thermal conductivity values of nanoparticles. In the same time, viscosity of fluid is changing and it affects the heat transfer enhancement. Studies on entropy generation of heat transfer in nanofluid filled energy systems are extremely limited. In this context, Shahi et al. [65] performed a numerical study on entropy generation due to natural convection of a nanofluid that consists of water and Cu in a cavity with a protruded heat source. They used finite volume method and solved the equations for different Rayleigh numbers, solid concentration and heat source location. Their results showed that the maximum value of Nusselt number and minimum entropy generation are obtained when heat source mountains in the bottom horizontal wall. Singh et al. [66] present a theoretical investigation of the entropy generation analysis due to flow and heat transfer in nanofluids. They considered the most common alumina–water nanofluids as the model fluid. They observed that at lower tube diameter, flow friction irreversibility is more significant and at higher tube diameter thermal irreversibility is more. For both laminar and turbulent flow, there is an optimum diameter at which the entropy generation rate is the minimum for a given nanofluid.

7. Conclusions

The present review is a comprehensive outlook on the research progress made on entropy generation in natural convection and mixed convection in ducts or channels. The important result can be drawn from the reviewed literature is that the main reasons of entropy generation are heat transfer and fluid friction in a thermal system with buoyancy force. From the observed results it is clearly seen, that analysis of entropy generation is crucial for all thermal systems to reduce energy and control of heat transfer and fluid flow. The most important parameter is Rayleigh number on entropy generation in natural convection. The entropy generation increases with increasing of Rayleigh number due to increasing of heat transfer and fluid friction. Entropy analysis indicates a local address that where energy losses high in the physical model or systems. Darcy number is also another effective parameter for entropy generation in porous media filled systems. The entropy also increases with increasing of Darcy number. In the case of mixed convection, the entropy generation decreases with increasing of Richardson number due to decreasing of heat transfer. Hartmann number is another effective parameter in magnetohydrodynamics studies with electrically conductive fluids. In this case, increasing of Hartmann number decreases the flow velocity. However, the entropy is reduced. Application direction of magnetic force is also important to minimize the entropy generation. Entropy generation decreases with decreasing of irreversibility ratio. Inclination angle makes important effect in natural convection studies due to heat transport way changes by gravity. In these kinds of studies, entropy generation is also affected. The geometrical shape and aspect ratio of the cavity change the entropy generation even at constant Rayleigh number. And type of the fluid with Prandtl number places important role. Recently, the second law thermodynamics was applied to industrial problems to minimize the entropy generation [60,61]. There are very few correlations between effective parameters and

entropy generation. Researcher can focus on that subject for future studies. The trend in the literature goes to extension of natural and mixed convection studies by adding entropy generation.

References

[1] Rosen MA. Second-law analysis: approach and implications. Int J Energy Res 1999;33:415–29.
[2] Bejan A. Second law analysis in heat transfer. Energy 1980;5:721–32.
[3] Havzali M, Arikoglu A, Komurgoz O, Keser HI, Ozkol I. Analytical–numerical analysis of entropy generation for gravity-driven inclined channel flow with initial transition and entrance effects. Phys Scr 2008;78:045401.
[4] Komurgoz G, Arikoglu A, Turker E, Ozkol I. Second-law analysis for an inclined channel containing porous-clear fluid layers by using the differential transform method. Num Heat Transf A 2010;57:603–23.
[5] Shuja SZ, Yilbas BS, Budair MO. Natural convection in a square cavity with a heat generating body: Entropy consideration. Heat Mass Transf 2000;36:343–50.
[6] Bejan A. Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture. Int J Energy Res 2002;26:545–65.
[7] Bejan A. A study of entropy generation in fundamentals convective heat transfer. ASME J Heat Transf 1979;101:718–25.
[8] Bejan A. Entropy generation minimization. Boca Raton: CRC Press; 1996.
[9] Bejan A. Entropy generation through heat and fluid flow. New York: Wiley; 1982.
[10] Mourad M, Hassen A, Nejib H, Ammar BB. Second law analysis in convective heat and mass transfer. Entropy 2006;8:1–17.
[11] Baytas AC. Entropy generation for natural convection in an inclined porous cavity. Int J Heat Mass Transf 2000;43:2089–99.
[12] Zahmatkesh I. On the importance of thermal boundary conditions in heat transfer and entropy generation for natural convection inside a porous enclosure. Int J Therm Sci 2008;47:339–46.
[13] San JY, Worek WM, Lavan Z. Entropy generation in convective heat transfer and isothermal convective mass transfer. J Heat Transf 1987;109:647–52.
[14] San JY, Worek WM, Lavan Z. Entropy generation in combined heat and mass transfer. Int J Heat Mass Transf 1987;30:1359–69.
[15] Bejan A. The concept of irreversibility in heat exchanger design counter flow heat exchangers for gas-to-gas applications. J Heat Transf 1977;99:334–80.
[16] Mahmud S, Fraser RA. The second law analysis in fundamental convective heat transfer problems. Int J Therm Sci 2003;42:177–86.
[17] Tsatsaronis G, Moran MJ, Cziesla F, Bruckner T, editors. Design optimization of thermal systems using exergy-based techniques, vol. III. Berlin: Germany; 2002. p. 1609–16.
[18] Şahin AZ. Irreversibilities in various duct geometries with constant wall heat flux and laminar flow. Energy Int J 1998;23(6):465–73.
[19] Varol Y, Oztop HF, Pop I. Entropy analysis due to conjugate-buoyant flow in a right-angle trapezoidal enclosure filled with a porous medium bounded by a solid vertical wall. Int J Therm Sci 2009;48:1161–75.
[20] Ingham DB, Pop I, editors. Transport Phenomena in Porous Media III. Oxford: Elsevier; 2005.
[21] Baytas AC, Baytas AF. Entropy generation in porous media. In: Transport Phenomena in Porous Media III. 2005. p. 201–26.
[22] Mahmud S, Fraser RA. Magnetohydrodynamic free convection and entropy generation in a square porous cavity. Int J Heat Mass Transf 2004;47:3245–56.
[23] Slimi K. Entropy generation for unsteady natural convection and radiation within a tilted saturated porous channel. Int J Exergy 2006;3:174–90.
[24] Varol Y, Oztop HF, Pop I. Entropy generation due to natural convection in non-uniformly heated porous isosceles triangular enclosures at different positions. Int J Heat Mass Transf 2009;52:1193–205.
[25] Baytaş AC. Entropy generation for thermal nonequilibrium natural convection with non-darcy flow model in a porous enclosure filled with a heat-generating solid phase. J Porous Media 2007;10:261–75.
[26] Mahmud S, Fraser RA. Free convection and irreversibility analysis inside a circular porous enclosure. Entropy 2003;5:358–65.
[27] Arpaci VS, Selamet A. Entropy efficiency of energy systems. Prog Energy Combust Sci 1992;18:429–45.
[28] Dagtekin I, Oztop HF, Bahloul A. Entropy generation for natural convection in Γ-shaped enclosures. Int Commun Heat Mass Transf 2007;34:502–10.
[29] Platten JK, Chavepeyer G. Influence de la thermodiffusion sur la naissance de la convection libreen configuration de Rayleigh-Bénard. Entropie 1994;184/185:23–6.
[30] Magherbi M, Abbassi H, Ben Brahim A. Entropy generation at the onset of natural convection. Int J Heat Mass Transf 2003;46:3441–50.
[31] Ilis GG, Mobedi M, Sunden B. Effect of aspect ratio on entropy generation in a rectangular cavity with differentially heated vertical walls. Int Commun Heat Mass Transf 2008;35:696–703.
[32] Abu-Hijleh BAK, Jadallah IN, Abu-Nada E. Entropy generation due to natural convection from a horizontal isothermal cylinder in oil. Int Commun Heat Mass Transf 1998;25:1135–43.
[33] Baytas AC. Optimisation in an inclined enclosure for minimum entropy generation in natural convection. J Non-Equilib Thermodyn 1997;22:145–55.
[34] Andreozzi A, Auletta A, Manca O. Entropy generation in natural convection in a symmetrically and uniformly heated vertical channel. Int J Heat Mass Transf 2006;49:3221–8.
[35] Erbay LB, Altaç Z, Sulus B. An analysis of the entropy generation in a square enclosure. Entropy 2003;5:496–505.
[36] Erbay LB, Altaç Z, Sülüş B. Entropy generation in a square enclosure heated from a vertical lateral wall. In: Proceedings of the 15th International Symposium on Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems: ECOS 2002. 2002.
[37] Erbay LB, Altac Z, Sulus B. Entropy generation in a square enclosure with partial heating from a vertical lateral wall. Heat Mass Transf 2004;40: 909–18.
[38] Carrington CG, Sun ZF. Second law analysis of combined heat and mass transfer in internal flow and external flows. Int J Heat Mass Transf 1992;13: 65–70.
[39] Varol Y, Oztop HF, Koca A, Avcı E. Forecasting of entropy production due to buoyant convection using support vector machines (SVM) in a partially cooled square cross-sectional room. Expert Syst Appl 2009;36:5813–21.
[40] Mukhopadhyay A. Analysis of entropy generation due to natural convection in square enclosures with multiple discrete heat sources. Int Commun Heat Mass Transfer, doi:10.1016/j.icheatmasstransfer.2010.05.007.
[41] Yang SA, Hung RY, Ho YY. Entropy generation analysis of free convection film condensation on a vertical ellipsoid with variable wall temperature. World Acad Sci Eng Technol 2007;33:189–94.
[42] Abu-Hijleh BAK, Abu-Qudais M, Abu-Nada E. Numerical prediction of entropy generation due to natural convection from a horizontal cylinder. Energy 1999;24:327–33.
[43] Jery AE, Hidouri N, Magherbi M, Ben Brahim A. Effect of an external oriented magnetic field on entropy generation in natural convection. Entropy 2010;10:1391–417.
[44] Narusawa U. The second-law analysis of mixed convection in rectangular ducts. Heat Mass Transf 2001;37:197–203.
[45] Yilbas BS, Shuja SZ, Iqbal MO. Energy and entropy analysis in a square cavity with protruding body: effects of protruding body aspect ratio. Int J Energy Res 2002;26:851–66.
[46] Abu-Hijleh BAK, Heilen WN. Entropy generation due to laminar natural convection over a heated rotating cylinder. Int J Heat Mass Transf 1999;42: 4225–33.
[47] Abbassi H, Magherbi M, Brahim AB. Entropy generation in Poiseuille–Benard channel flow. Int J Therm Sci 2003;42:1081–8.
[48] Nourollahi M, Farhadi M, Sedighi K. Numerical study of mixed convection and entropy generation in the Poiseulle–Benard channel in different angles. Therm Sci 2010;14:329–40.
[49] Mahmud S, Fraser RA. Vibrational effect on entropy generation in a square porous cavity. Entropy 2003;5:366–76.
[50] Shohel M, Roydon AF. Analysis of mixed convection–radiation interaction in a vertical channel: entropy generation. Exergy Int J 2002;2:330–9.
[51] Cheng CH, Ma WP, Huang WH. Numerical predictions of entropy generation for mixed convective flows in a vertical channel with transverse fin arrays. Int J Heat Mass Transf 1994;21:519–30.
[52] Famouri M, Hooman K. Entropy generation for natural convection by heated partitions in a cavity. Int Commun Heat Mass Transf 2008;35:492–502.
[53] Mahmud S, Sadrul Islam AKM. Laminar free convection and entropy generation inside an inclined wavy enclosure. Int J Therm Sci 2003;42:1003–12.
[54] Varol Y, Oztop HF, Koca A. Entropy production due to free convection in partially heated isosceles triangular enclosures. Appl Therm Eng 2008;28:1502–13.
[55] Varol Y, Oztop HF, Koca A. Entropy generation due to conjugate natural convection in enclosures bounded by vertical solid walls with different thicknesses. Int Commun Heat Mass Transf 2008;35:648–56.
[56] Mahmud S, Fraser RA. Mixed convection–radiation interaction in a vertical porous channel: entropy generation. Energy 2003;28:1557–77.
[57] Yilbas BS, Shuja SZ, Gbadebo SA, Abu Al-Hamayel HI, Boran K. Natural convection and entropy generation in a square cavity. Int J Energy Res 1998;22:1275–90.
[58] Bassam AKAH. Entropy generation due to natural convection from a horizontal isothermal cylinder in oil. Int Commun Heat Mass Transf 1998;25:1135–43.
[59] Mahmud S, Tasnim SH, Mamun MAH. Thermodynamic analysis of mixed convection in a channel with transverse hydromagnetic effect. Int J Therm Sci 2003;42:731–40.
[60] Yilbas BS. Laser short-pulse of gold–silver assembly: entropy generation due to heat and electricity flows in electron subsystem. Numer Heat Transf A 2006;49:873–91.
[61] Naphon P. On the performance and entropy generation of the double-pass solar air heater with longitudinal fins. Renew Energy 2005;30:1345–57.
[62] Patankar SV. Numerical heat transfer and fluid flow. New York: Hemisphere; 1980.
[63] Prigogine I. Etude thermodynamique des processus irreversibles. 4th edn. Desoer: Liège; 1967.
[64] Oztop HF. Effective parameters on second law analysis for semicircular ducts in laminar flow and constant wall heat flux. Int Commun Heat Mass Transf 2005;32:266–74.
[65] Shahi M, Mahmoudi AH, Raouf AH. Entropy generation due to natural convection cooling of a nanofluid. Int Commun Heat Mass Transf 2011;38: 972–83.
[66] Singh PK, Anoop KB, Sundararajan T, Das SK. Entropy generation due to flow and heat transfer in nanofluids. Int J Heat Mass Transf 2010;53:4757–67.
[67] Chen CK, Lai HY, Liu CC. Numerical analysis of entropy generation in mixed convection flow with viscous dissipation effects in vertical channel. Int Commun Heat Mass Transf 2011;38:285–90.

[68] Kaluri RM, Basak T. Analysis of entropy generation for distributed heating in processing of materials by thermal convection. Int J Heat Mass Transf 2011;54:2578–94.
[69] Oliveski RDC, Macgnan MH, Copetti JB. Entropy generation and natural convection in rectangular cavities. Appl Therm Eng 2009;29:1417–25.
[70] Saleem M, Hossain MdA, Mahmud S, Pop I. Entropy generation in Marangoni convection flow of heated fluid in an open ended cavity. Int J Heat Mass Transf 2011;54:4473–84.
[71] Kaluri RS, Basak T. Entropy generation minimization versus thermal mixing due to natural convection in differentially and discretely heated square cavities. Numer Heat Transf A 2010;58:475–504.
[72] Basak T, Kaluri RS, Balakrishnan AR. Effects of thermal boundary conditions on entropy generation during natural convection. Numer Heat Transf A 2011;59:372–402.
[73] Amani E, Nobari MRH. A numerical investigation of entropy generation in the entrance region of curved pipes at constant wall temperature. Energy 2011;36:4909–18.
[74] Hernandez VHR, Ascencio CD, Robles DJ, Munoz AG, Aguilar AZ, Mora HP. Entropy generation analysis of a proton exchange membrane fuel cell (PEMFC) with a fermat spiral as a flow distributor. Energy 2011;36:4864–70.